BROOKHAVEN NATIONAL LABORATORY

Superconducting Magnet Division

Magnet Note

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Topic: Miscellaneous

Title: AC Loss Measurements in RHIC Dipoles

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AC LOSS MEASUREMENTS IN RHIC DIPOLES

This tech note contains memos documenting AC loss measurements made in RHIC and SSC arc dipoles in the early 1990's. The most recent memo, dated August 1, 1994, contains a table summarizing all the measurements in these magnets except for the measurement of DRE012, which is reported in a memo dated August 19, 1993.

All the RHIC magnets measured were full length (~10 m). DRD009, DRD 010, and DRE011 were three of the last four full-length models built in the R&D program. DRG 102, 103 and 111 were production models built at Grumman. Construction differences between the different model numbers are small and not expected to affect the energy loss measurement very much. The measured values are very similar, as would be expected. The inductance of these magnets is 28 mH.

The DCA3xx magnets were made at Fermilab and the DCA2xx magnets made at BNL. The memo dated December 28, 1992 documents a comparison of the energy loss made at BNL and Fermilab. The measurements agreed – an important result, since the energy loss is such a small fraction of the energy at full field, so that perturbations to the ramp (different at the two labs) could have been important. The inductance of the SSC magnets was 76 mH.

BROOKHAVEN NATIONAL LABORATORY

MEMORANDUM

Date: September 29, 1992

To: Joe Muratore, Peter Wanderer

From: Richard Thomas, 902B, ×3534

Subject: DRD009 — AC Loss Measurements

AC loss data were acquired at nominal ramp rates of 16, 24, 32, 48, 64, 96, and 128 A/s. (For ramp rates higher than 32 A/s, the actual rate turns out to be higher than the requested ramp rate.) Eighteen data points were collected, but the first was discarded. In the future, we will "condition" a magnet by running it through the 500 A to 5000 A trapezoidal ramping cycle two or three times before beginning to collect data.

Points in Fit	**Intercept** (kJ/cycle)	**Slope** $\left(\frac{J/cycle}{A/s}\right)$	**Average Absolute Deviation** (kJ/cycle)
DRD009			
29 September 1992 (17 points)	0.344	1.58	0.021
DCA211			
09 September 1992 (9 points)	1.230	2.79	0.039
DCA213			
24 July 1992 (15 points)	1.116	7.91	0.057
07 August 1992 (12 points)	1.141	7.76	0.050
All data points	1.115	7.94	0.054

There is one significant change in the program for the measurements on DRD009 as compared to the previous measurements. The output frequency of the Wavetek Signal Generator was measured and found to vary by as much as 1.7% from a given programmed setting. However, the ratio of the output frequency to any specific setting can be measured and the programmed setting changed to give an output that differs from the desired output frequency by less than ±0.3%. The Wavetek Signal Generator is used to trigger the two digital multimeters simultaneously at a rate that allows maximum coverage of the V and I waveforms.

Consequently, it becomes the time base for the experiment. As the desired triggering frequencies are known and are only ten in number, a correction is now applied to obtain actual output frequencies that are closer to the desired triggering frequencies.

For DCA211 there wasn't adequate time to acquire enough data to determine the intercept or slope accurately. (A lot of taps had to be changed before loss measurements could start, and there were more pressing experimental procedures still to be performed.) Only nine data points at three ramp rates (32, 48, and 64 A/s) were obtained. It is hoped that data over a wider range of ramp rates will be collected on this magnet in the future.

The inductance of DRD009 was about 28 mH while that of DCA211 and DCA213 was about 76 mH. If the designs were similar and the)*B* for the cycles the same, the intercept values would approximately scale with the inductance. However, the designs aren't all that similar.

Saturation effects were more prominent in the voltage waveform of DRD009 than in the voltage waveforms of the SSC magnets. (Since dI/dt is constant, the droop in the voltage waveform at high I is a consequence of a decreasing L at increasingly high fields.) An estimate of the saturation as a function of current could be obtained by fitting a curve to data derived from the voltage waveform.

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MEMORANDUM

Date: December 28, 1992

To: Joe Muratore, Peter Wanderer, Bill Sampson, Arup Ghosh

From: Richard Thomas, 902B, ×3534

Subject: DCA312 — AC Loss Measurements

On 23 December 1992, AC loss data were acquired for Fermilab SSC Dipole Magnet DCA312 at nominal ramp rates of 16, 24, 32, 48, 64 and 76 A/s. The first attempt to measure the loss at a nominal rate of 96 A/s failed because the taps on the power supply transformers have to be changed for high ramp rates and magnets with large inductance. (The inductance of the SSC dipole is about 76 mH while that of a RHIC dipole is only 28 mH.) The ac losses in DCA312 were strongly dependent on the ramp rate, and the next attempt at 96 A/s resulted in the magnet quenching at 4934 A. (At higher ramp rates, the power supply ramps more quickly than requested. The actual rate was 101.5 A/s when the quench occurred.)

BROOKHAVEN NATIONAL LABORATORY

MEMORANDUM

Date: December 28, 1992

To: Joe Muratore, Peter Wanderer, Bill Sampson, Arup Ghosh

From: Richard Thomas, 902B, ×3534

Subject: DRD010 — AC Loss Measurements

On 2 December 1992, AC loss data were acquired for RHIC Dipole Magnet DRD010 at nominal ramp rates of 16, 24, 32, 48, 64, 96, and 128 A/s. (For ramp rates higher than 32 A/s, the actual rate turns out to be higher than the requested ramp rate.) The slope of the Loss (in kJ/cycle) versus Ramp Rate plot was smaller than that for DRD009.

Points in Fit	**Intercept** (kJ/cycle)	**Slope** $\left(\frac{J/cycle}{A/s}\right)$	**Average Absolute Deviation** (kJ/cycle)
DRD009			
29 September 1992 (17 points)	0.344	1.58	0.021
DRD010			
02 December 1992 (24 points)	0.389	0.46	0.025
DCA211			
09 September 1992 (9 points)	1.230	2.79	0.039
DCA213			
24 July 1992 (15 points)	1.116	7.91	0.057
07 August 1992 (12 points)	1.141	7.76	0.050
All data points	1.115	7.94	0.054

BROOKHAVEN NATIONAL LABORATORY

MEMORANDUM

Date: May 19, 1993

To: Joe Muratore, Peter Wanderer, Phil Radusewicz, Arnaud Devred, Bill Sampson, Arup Ghosh

From: Richard Thomas, 902B, ×3534

Subject: DCA318 - AC Loss Measurements

On 19 May 1993, AC loss data were acquired for Fermilab SSC Dipole Magnet DCA318 at nominal ramp rates of 16, 24, 32, 48, 64 and 76 A/s. Measurements can not be taken at higher ramp rates without reconfiguring the "free-wheeling diodes and dump resistor." The ac losses of this dipole magnet are not a strong function of ramp rate, so, if a more precise determination of the slope of the plotted losses is desired, measurements at higher ramp rates would be useful.

Points in Fit	**Intercept** *(kJ/cycle)*	**Slope** $\left(\frac{J/cycle}{A/s}\right)$	**Average Absolute Deviation** *(kJ/cycle)*
DRD009			
29 September 1992 (17 points)	0.344	1.58	0.021
DRD010			
02 December 1992 (24 points)	0.389	0.46	0.025
DCA211			
09 September 1992 (9 points)	1.230	2.79	0.039
DCA213			
24 July 1992 (15 points)	1.116	7.91	0.057
07 August 1992 (12 points)	1.141	7.76	0.050
All data points	1.115	7.94	0.054
DCA312			
23 December 1992 (17 points)	1.184	60.37	0.040
DCA318			
19 May 1993 (24 points)	1.149	3.00	0.047

The ramp rate dependence for DCA318 was less than half that of DCA213 and similar to that for DCA211. However, the data for DCA211 covered only a narrow range of ramp rates (33, 50, and 67 A/s), so the slope was not accurately determined for that magnet.

As always, the voltage signal contained many spikes.[1] These spikes are not the result of noise and are not present during the dwell periods at 500 A and 5000 A. Since the output current of the power supply is digitally controlled, the magnet current is not actually ramped. It is instead gradually increased or decreased in small steps. The large spikes are almost certainly a result of a non-linearity in the D/A convertor that generates the current ramp. The smaller spikes are presumably from the current steps themselves, although this has not been verified. (It is not appropriate to ignore the spikes or to filter the data digitally to remove them. These spikes produce dI/dt blips, and the resulting high rates of change of the current cause real high rates of change in the instantaneous power.) Also, the frequency of the spikes is ramp-rate dependent. This is almost certainly the result of the algorithm used to generate the voltage outputs of the D/A convertor for the power supply current ramps. Neither the algorithm nor the particular model of computer-controlled D/A convertor has been optimized to produce the smoothest possible current ramps.

Depending on the effort involved, it might be interesting to use one of the newer IOtech DAC488HR convertors and a better algorithm to see how minimizing the size of the power supply current steps affects the ac loss measurements (as well as other ramp-dependent measurements). It may be that the negative blips for the current steps on the ramp down compensate for the positive ones on the way up, and the ramp rate variation about a nominal constant rate isn't all that important overall. For the integral coil and saturation magnetization measurements, the current steps *have* been minimized for the power supply systems that will be used.

[1]Memoranda dated 04 January 1993 and 05 January 1993 went into detail about these spikes and showed graphs of) I vs. t.

[1]Memoranda dated 04 January 1993 and 05 January 1993 went into detail about these spikes and showed graphs of) I vs. t.

BROOKHAVEN NATIONAL LABORATORY

MEMORANDUM

Date	July 13, 1993
To	Joe Muratore, Peter Wanderer, Bill Sampson, Arup Ghosh
From	Richard Thomas, 902B, ×3534, Pager 4149 (digital)
Subject	DRE011 - AC Loss Measurements

On 13 July 1993, AC loss data were acquired for RHIC Dipole Magnet DRE011 at ramp rates of 16, 49, 66, 102, and 138 A/s. The ramp-rate dependence of the AC losses for this

Points in Fit	Intercept *(kJ/cycle)*	Slope $\left(\frac{J/cycle}{A/s}\right)$	Average Absolute Deviation *(kJ/cycle)*
DRD009			
29 September 1992 (17 points)	0.344	1.58	0.021
DRD010			
02 December 1992 (24 points)	0.389	0.46	0.025
DRE011			
13 July 1993 (21 points)	0.369	1.75	0.025
DCA211			
09 September 1992 (9 points)	1.230	2.79	0.039
DCA213			
24 July 1992 (15 points)	1.116	7.91	0.057
07 August 1992 (12 points)	1.141	7.76	0.050
All data points	1.115	7.94	0.054
DCA312			
23 December 1992 (17 points)	1.184	60.37	0.040
DCA318			
19 May 1993 (24 points)	1.149	3.00	0.047
19 May, 01 June & 02 June 1993 (50 points)	1.135	3.85	0.057

dipole magnet is similar to that of DRD009 (DRE011's slope is 11% higher) and is 3.8 times that of dipole DRD010.

The measurements were taken using the old regulator card. This card had a new DAC installed in May, so the large spikes that were previously observed are no longer present. This regulator card does produce overshoots at the beginning and end of the ramp. A new regulator card is available which produces smaller overshoots, but these have a long fall time. The fall time for the overshoots with the new card is so long that constant current values are not obtained within the 5 s dwells at the top or at the end of the ramp, so this card was not used.

BROOKHAVEN NATIONAL LABORATORY
MEMORANDUM

Date July 29, 1993

To Joe Muratore, Peter Wanderer, Animesh Jain, George Ganetis, Bill Sampson, Arup Ghosh

From Richard Thomas, 902B, ×3534, Pager 4149 (digital)

Subject DCA317 - AC Loss Measurements

On 27-28 July 1993, AC loss data were acquired for the FermiLab SSC Dipole Magnet DCA317 at ramp rates of 16, 32, 49, 66, 76, 102, 127, 153, 170, 191, and 218 A/s. The ramp-rate dependence of the AC losses for this dipole magnet is similar to that of DCA318.

The measurements were taken using the old regulator card. This card had a new DAC installed in May, so the large spikes that were previously observed are no longer present. This regulator card does produce overshoots at the beginning and end of the ramp. If the beginning and ending currents are identical and if the large d*I*/dt's that occur at the beginning and end of the ramps do not contribute significantly to the real losses, the overshoots probably have little effect on the computed losses. Significant amounts of inductive energy (*B*-field) do flow into and out of the magnet during the top dwell and end dwell periods. These dwell periods must therefore be included in the analysis.

The average real power dissipated in the magnet over the entire measurement time is calculated. The "measurement time" includes all three dwell periods. The quantity plotted is the real energy loss which is obtained by multiplying the average real power dissipated by the measurement time. The dwells are specified to be 5 s, but usually turn out to be more like 8 s long.

(I don't know why the VAX Main Power Supply program is so poor at timing the dwells and at producing the requested ramp rates. If a ramp rate of 16 or 32 A/s is requested, that is about what you get, but if you ask for 64 A/s, you get 66 A/s. Similarly, a request for 200 A/s produces 216 A/s, but 300 A/s gives 304 A/s, and if you ask for 400 A/s, you get 507 A/s! I suspect there may be some flaw in either the algorithm or the method.)

It is certain that there is little real energy loss during the initial and final dwells at 500 A, and it is probably true that the real energy loss during the top dwell at 5000 A is also small relative to the losses during the ramps up and down. If the average power loss were plotted, it would be sensitive to the time spent during the dwells as compared to the time spent ramping up or down. Instead, the average energy loss is plotted which does not have this sensitivity.

The plots produced by the HP program fit the data to a line by minimizing the sum of the absolute deviations (and thus the fit is less strongly influenced by outliers). Using Excel to fit the data, which uses the convential minimization of the sum of the squares of the deviations, gives 1.154 kJ/cycle for the intercept (compared to 1.172) and 3.86 (J/cycle)/(A/s) for the slope (compared to 3.69). If it is assumed that the errors in the data points obtained have a normal distribution, then with 90% confidence, the intercept lies between 1.124 and 1.184 kJ/cycle, and the slope lies between 3.63 and 4.09 (J/cycle)/(A/s).

Points in Fit	**Intercept** *(kJ/cycle)*	**Slope** $\left(\frac{J/cycle}{A/s}\right)$	**Average Absolute Deviation** *(kJ/cycle)*
DRD009			
29 September 1992 (17 points)	0.344	1.58	0.021
DRD010			
02 December 1992 (24 points)	0.389	0.46	0.025
DRE011			
13 July 1993 (21 points)	0.369	1.75	0.025
DCA211			
09 September 1992 (9 points)	1.230	2.79	0.039
DCA213			
24 July 1992 (15 points)	1.116	7.91	0.057
07 August 1992 (12 points)	1.141	7.76	0.050
All data points	1.115	7.94	0.054
DCA312			
23 December 1992 (17 points)	1.184	60.37	0.040
DCA317			
27-28 July 1993 (40 points)	1.172	3.69	0.039
DCA318			
19 May 1993 (24 points)	1.149	3.00	0.047
19 May, 01 June & 02 June 1993 (50 points)	1.135	3.85	0.057

BROOKHAVEN NATIONAL LABORATORY

MEMORANDUM

Date August 19, 1993

To Joe Muratore, Peter Wanderer, Bill Sampson, Arup Ghosh, Erich Willen

From Richard Thomas, 902B, ×3534, Pager 4149 (digital)

Subject DRE012 - AC Loss Measurements

On 18 August 1993, AC loss data were acquired for RHIC Dipole Magnet DRE012 at ramp rates of 20, 30, 40, 51, 61, 69, 80, and 102 A/s. The ramp-rate dependence of the AC losses for this dipole magnet is similar to that of DRE011 but the slope is 30% higher. (Note that the magnitude of the slopes for all the RHIC magnets has been small.) The slope is usually assumed to be proportional to the eddy current losses.

The measurements were taken using the old regulator card. This card had a new DAC installed in May, so the large spikes that were previously observed are no longer present. This regulator card does produce overshoots at the beginning and end of the ramp.

There was one significant change in how the data were acquired. The number of power line cycles over which each digital voltmeter reading was integrated was increased to 10. Previously the number of power line cycles was made no larger than the value required to reduce the total number of data points taken over a cylce to less than 5000 points. The accuracy of each reading should be improved by the use of a larger number of power line cycles per reading. Note that the average absolute deviation of the points from the fitted line was about 2.5 times smaller than that obtained for previously measured RHIC dipole magnets.

The plots produced by the HP program fit the data to a line by minimizing the sum of the absolute deviations (and thus the fit is less strongly influenced by outliers). Using Excel to fit the data, which uses the conventional minimization of the sum of the squares of the deviations, gives 0.354 kJ/cycle for the intercept (compared to 0.357) and 2.34 (J/cycle)/(A/s) for the slope (compared to 2.30). If it is assumed that the errors in the data points obtained have a normal distribution, then with 90% confidence, the intercept lies between 0.344 and 0.364 kJ/cycle, and the slope lies between 2.19 and 2.50 (J/cycle)/(A/s).

Points in Fit	Intercept (kJ/cycle)	Slope $\left(\frac{J/cycle}{A/s}\right)$	Average Absolute Deviation (kJ/cycle)
DRD009			
29 September 1992 (17 points)	0.344	1.58	0.021
DRD010			
02 December 1992 (24 points)	0.389	0.46	0.025
DRE011			
13 July 1993 (21 points)	0.369	1.75	0.025
DRE012			
18 August 1993 (27 points)	0.357	2.30	0.009
DCA211			
09 September 1992 (9 points)	1.230[¶]	2.79[¶]	0.039
DCA213			
24 July 1992 (15 points)	1.116	7.91	0.057
07 August 1992 (12 points)	1.141	7.76	0.050
All data points	1.115	7.94	0.054
DCA312			
23 December 1992 (17 points)	1.184	60.37	0.040
DCA317			
27-28 July 1993 (40 points)	1.172	3.69	0.039
DCA318			
19 May 1993 (24 points)	1.149	3.00	0.047
19 May, 01 June & 02 June 1993 (50 points)	1.135	3.85	0.057

[¶]Too few points to accurately determine slope or intercept.

BROOKHAVEN NATIONAL LABORATORY

MEMORANDUM

Date: June 13, 1994

To: Joe Muratore, Peter Wanderer, Animesh Jain, Bill Sampson, Arup Ghosh

From: Richard Thomas, 902B, ×3534, Pager 4149 (digital)

Subject: DRG111 — AC Loss Measurements

On 10 June 1994, AC loss data were acquired for the Northrop-Grumman RHIC Dipole Magnet DRG111 at ramp rates of 20, 31, 40, 51, 61, 69, 80, and 101 A/s. The results for this dipole magnet are similar to those for DRD009.

For each ramp rate, after a dwell time at 500 A, the current is ramped up to 5000 A, a second dwell at 5000 A occurs, then the current is ramped down (at the same rate as the up ramp rate) to 500 A where another dwell occurs. The regulator card for the power supply produces overshoots at the beginning and end of the ramps. If the beginning and ending currents are identical and if the large d*I*/dt's that occur at the beginning and end of the ramps do not contribute significantly to the real losses, the overshoots probably have little effect on the computed losses. Significant amounts of inductive energy (*B*-field) do flow into and out of the magnet during the top-dwell and end-dwell periods. These dwell periods must therefore be included in the analysis.

The average real power dissipated in the magnet over the entire measurement time is calculated by summing the instantaneous power readings ($V \cdot I$). The "measurement time" includes all three dwell periods. The quantity plotted is the real energy loss which is obtained by multiplying the average real power dissipated by the measurement time. The dwells are specified to be 5 s, but usually turn out to be more like 8 s long.

The plots produced by the HP program fit the data to a line by minimizing the sum of the absolute deviations (and thus the fit is less strongly influenced by outliers). Using Excel to fit the data, which uses the conventional minimization of the sum of the squares of the deviations, gives 327 J/cycle for the intercept (compared to 326) and 1.30 (J/cycle)/(A/s) for the slope (compared to 1.33). If it is assumed that the errors in the data points obtained have a normal distribution, then with 90% confidence, the intercept lies between 320 and 334 J/cycle, and the slope lies between 1.19 and 1.40 (J/cycle)/(A/s).

Fermilab Filter Measurements

Experiments were also performed using the two filters that were used during Fermi lab measurements on SSC magnets. At Fermilab, HP 3457A Digital Multimeters were used instead of HP 3458A's. These meters take longer to store each measurement, so there is a longer dead time between measurement points. The filters were reported to be well-matched and had no markings to distinguish one from the other. At BNL, one was labelled "A" and the other "B."

First, five measurements were performed in the usual way at 80 A/s without the filters. Each measurement was made up of 798 readings spaced 0.169 seconds apart. For each reading, the A/D convertor of the DVM integrated the input signal over ten power line cycles (0.167 s). Any signal fluctuations occurring during the two ms dead times are not sampled, but this is only 1.2% of the cycle. The average ac loss per cycle for these five measurements was 431.4 J/cycle with a standard deviation of 5.9 J/cycle.

Next, Filter "A" was inserted in the signal path for the *I* (current) signal, and Filter "B" inserted in the path of the *V* signal. The average ac loss per cycle for three measurements was reported to be 273.7 J/cycle with a standard deviation of 1.9 J/cycle.

Finally, the roles of the filters were reversed (Filter "A" was inserted in the *V* signal path, etc.). The average ac loss per cycle again changed. This time, the average loss for three measurements was calculated to be 308.4 J/cycle with a standard deviation of 2.7 J/cycle.

The filters must in some way alter the relative phase or amplitude of the *V* and *I* signals. A close inspection of the data points for the three test conditions and an inter-comparison of the different sets of points did not reveal any differences that could be the cause of the differing answers.

No Filters	**Filter A to I DVM**	**Filter A to V DVM**
433.0	275.1	308.2
435.0	274.5	311.1
435.6	271.5	305.8
432.0		
421.2		
431.4	273.7	308.4
5.9 *std. dev.*	1.9 *std. dev.*	2.7 *std. dev.*

Points in Fit	Intercept *(J/cycle)*	Slope $\left(\frac{J/cycle}{A/s}\right)$	Average Absolute Deviation *(J/cycle)*
DRD009			
29 September 1992 (17 points)	344	1.58	21
DRD010			
02 December 1992 (24 points)	389	0.46	25
DRE011			
13 July 1993 (21 points)	369	1.75	25
DRG111			
10 June 1994 (30 points)	326	1.33	6
DCA211			
09 September 1992 (9 points)	1,230	2.79	39
DCA213			
24 July 1992 (15 points)	1,116	7.91	57
07 August 1992 (12 points)	1,141	7.76	50
All data points	1,115	7.94	54
DCA312			
23 December 1992 (17 points)	1,184	60.37	40
DCA317			
27-28 July 1993 (40 points)	1,172	3.69	39
DCA318			
19 May 1993 (24 points)	1,149	3.00	47
19 May, 01 June & 02 June 1993 (50 points)	1,135	3.85	57

BROOKHAVEN NATIONAL LABORATORY

MEMORANDUM

DATE: July 11, 1994

TO: Joe Muratore, Peter Wanderer, Animesh Jain, Bill Sampson, Arup Ghosh

FROM: Richard Thomas, 902B, ×3534, Pager 4149 (digital)

SUBJECT: DRG102 — AC Loss Measurements

On 08 July 1994, AC loss data were acquired for the Northrop-Grumman RHIC Dipole Magnet DRG102 at ramp rates of 20, 31, 40, 51, 61, 70, 80, and 102 A/s. The results for this dipole magnet are similar to those for DRG111.

For each ramp rate, after a dwell time at 500 A, the current is ramped up to 5000 A, a second dwell at 5000 A occurs, then the current is ramped down (at the same rate as the up ramp rate) to 500 A where another dwell occurs. The regulator card for the power supply produces overshoots at the beginning and end of the ramps. If the beginning and ending currents are identical and if the large d*I*/dt's that occur at the beginning and end of the ramps do not contribute significantly to the real losses, the overshoots probably have little effect on the computed losses. Significant amounts of inductive energy (*B*-field) do flow into and out of the magnet during the top-dwell and end-dwell periods. These dwell periods must therefore be included in the analysis.

The average real power dissipated in the magnet over the entire measurement time is calculated by summing the instantaneous power readings (*V* @ *I*). The "measurement time" includes all three dwell periods. The quantity plotted is the real energy loss which is obtained by multiplying the average real power dissipated by the measurement time.

The plots produced by the HP program fit the data to a line by minimizing the sum of the absolute deviations (and thus the fit is less strongly influenced by outliers). Using Excel to fit the data, which uses the conventional minimization of the sum of the squares of the deviations, gives 338 J/cycle for the intercept (compared to 340) and 1.17 (J/cycle)/(A/s) for the slope (compared to 1.16). If it is assumed that the errors in the data points obtained have a normal distribution, then with 90% confidence, the intercept lies between 330 and 347 J/cycle, and the slope lies between 1.03 and 1.31 (J/cycle)/(A/s).

Fermilab Filter Measurements

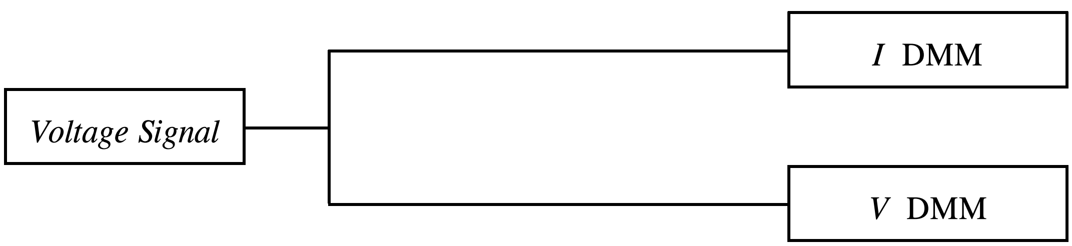
Additional experiments were performed using the two 4-Hz filters that were used during FermiLab measurements on SSC magnets. The filters, reported to be well-matched and originally not marked so as to distinguish one from the other, were labelled "A" and "B" at BNL.

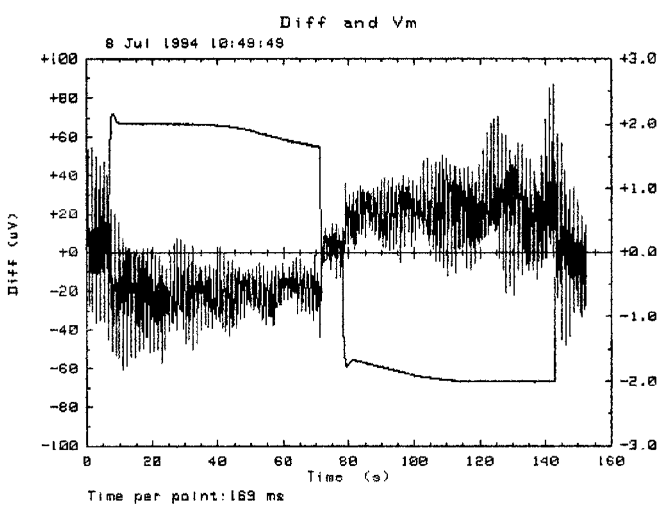
The purpose of the measurements were to see whether the two filters were identical, where "identical" means "having the same effect on the V and I signals produced by ramping the current in RHIC Dipole Magnet DRG102."

Six measurements were performed using the configurations indicated. The ramp rate was about 61 A/s for all the tests.

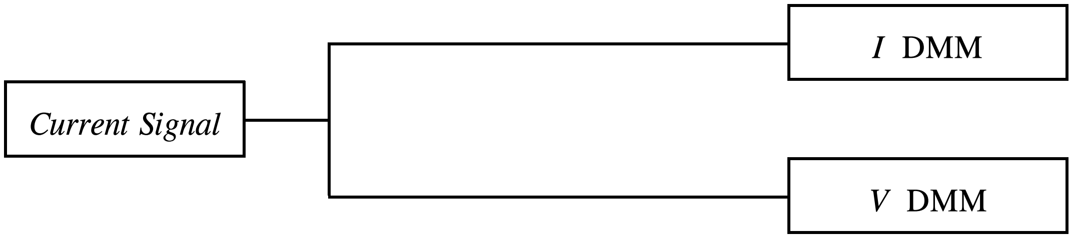
Note that these tests will also reveal any differences between the two HP 3458A Digital MultiMeters themselves. (The meters have *not* been recently calibrated.) We have six of these meters, and which two are used for a set of ac loss measurements is arbitrary. The digital multimeters used by the Control Room magnetic measurements group are listed in the table that follows the plots. The two meters without the "high stability reference" option are generally used for performing ring sample measurements on magnet steel in Room 37; however, one of them is borrowed for measurements with the new ac-ramp magnetic measurements program where a RHIC air mole is used.

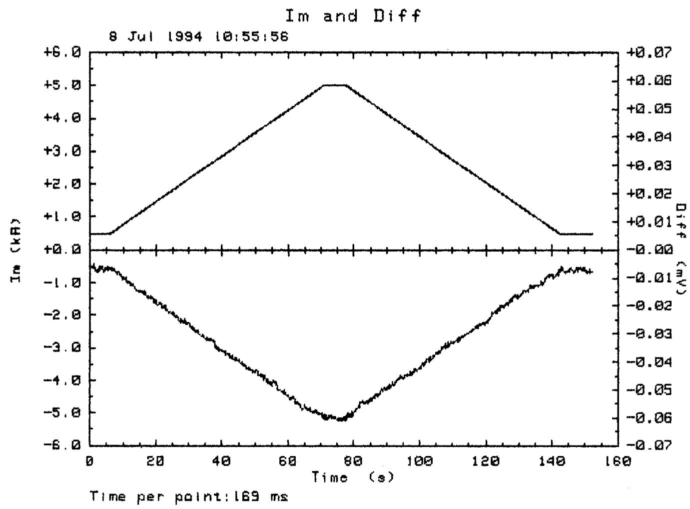
Each meter acquires 905 readings spaced ~0.169 ms apart (10/60 + 0.002 s). (A reading is the average voltage seen at the input terminals of the meter over ten power line cycles. A power line cycle is not actually 1/60 s, but is instead the period of the actual ac input power to the meter to the nearest 100 ns as measured by the DMM. On 08 July 1994, the power line frequency was slightly less than 60 Hz.)



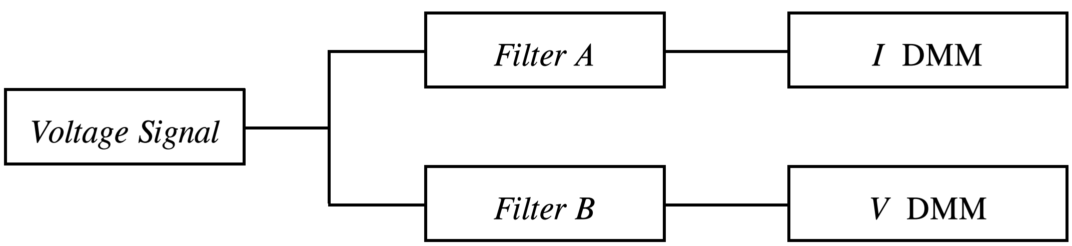


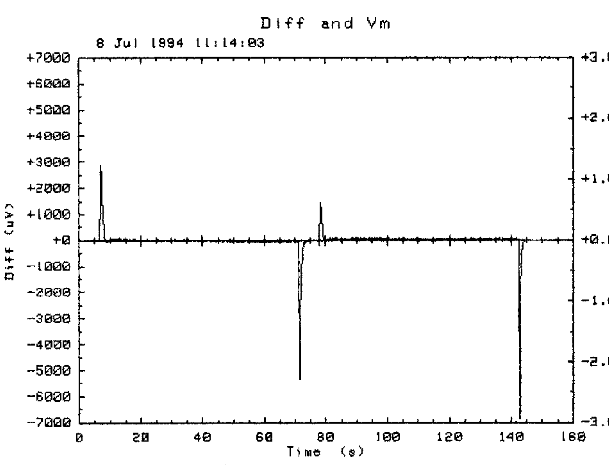
The plot above shows that the difference in the readings (*Im ! Vm)* of the two meters was generally ~25 μV. The voltage signal itself was about 2.16 V. As the difference changes sign when the input voltage changes sign, the error can be attributed to a difference in gain with the gain of the V DMM being larger than that of the I DMM.

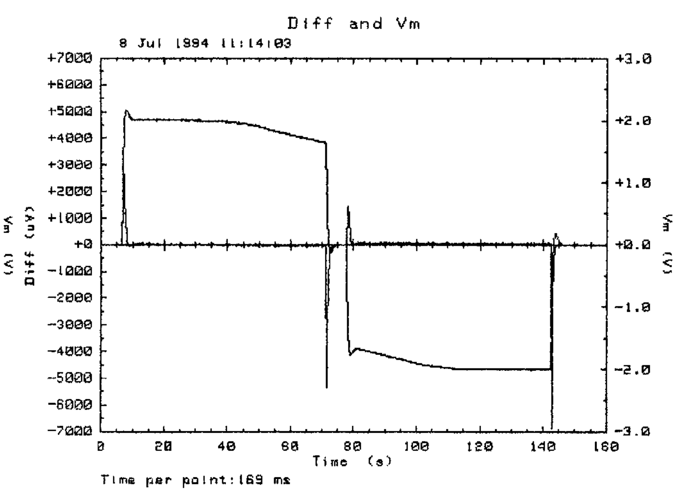




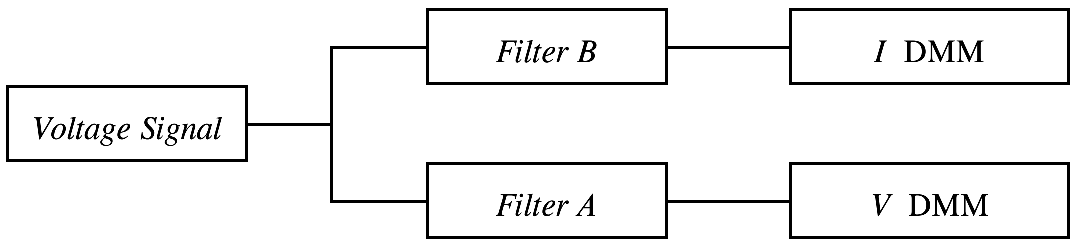
We see a similar gain error in the plot for the current signal. (The current signal is from the current transducer, an active device, and has a maximum amplitude of ~5 V.) The gain of the *V* DMM can be seen to be about 0.0012% higher than the gain of the *I* DMM.

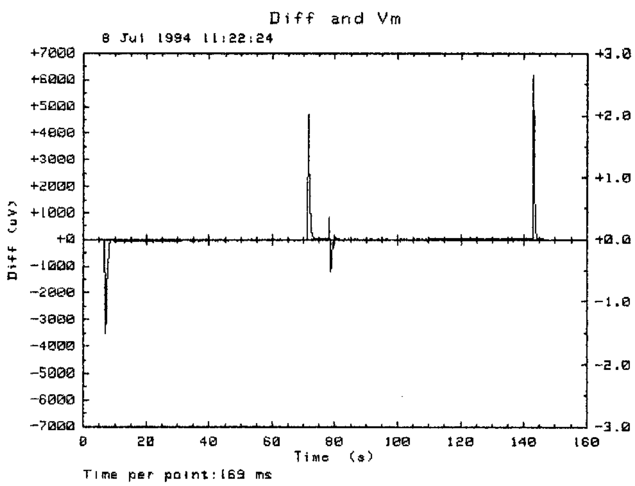


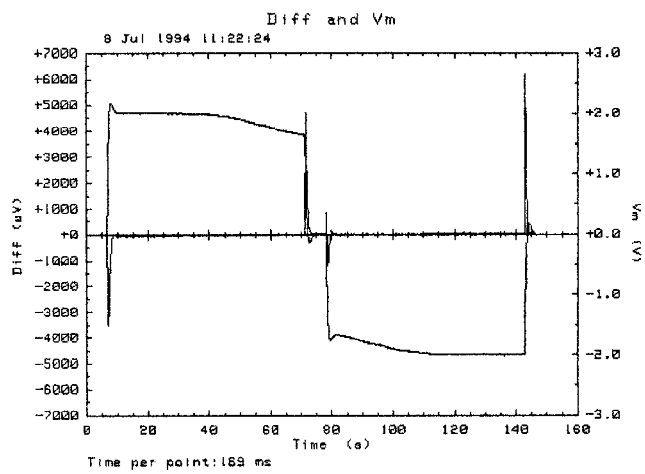




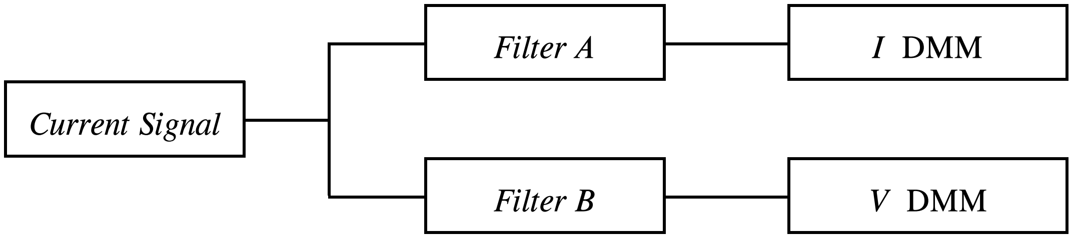
In the first plot on the preceding page, only the difference signal is shown so that it is not obscured by the the plot of the actual input signal. It is clear that the filters are not well-matched, (or at least, they are no longer well-matched). A difference of nearly 7 mV is seen at the point where the down ramp ends. The voltage signal is, as expected, “square-wave”-like, and therefore contains many high frequency components. The difference plot indicates that the two 4-Hz filters do not uniformly attenuate the amplitudes of these high frequency components.

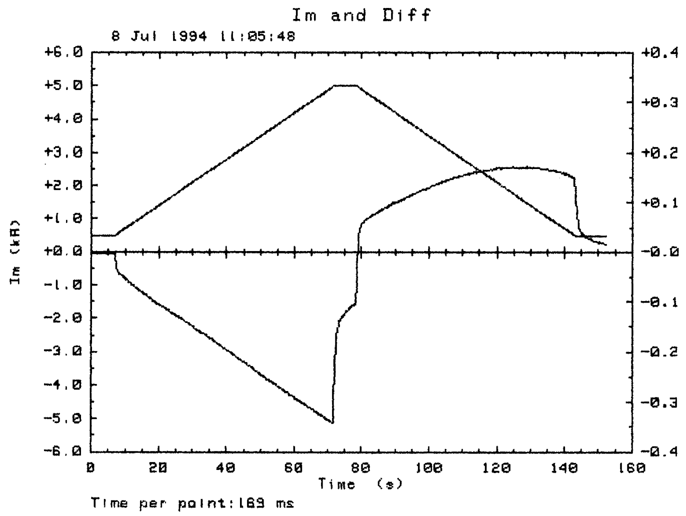




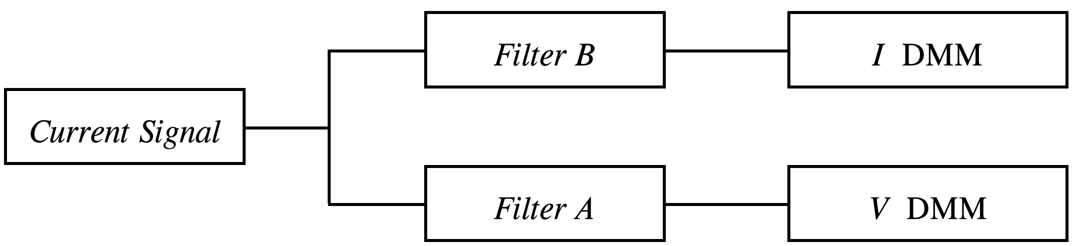


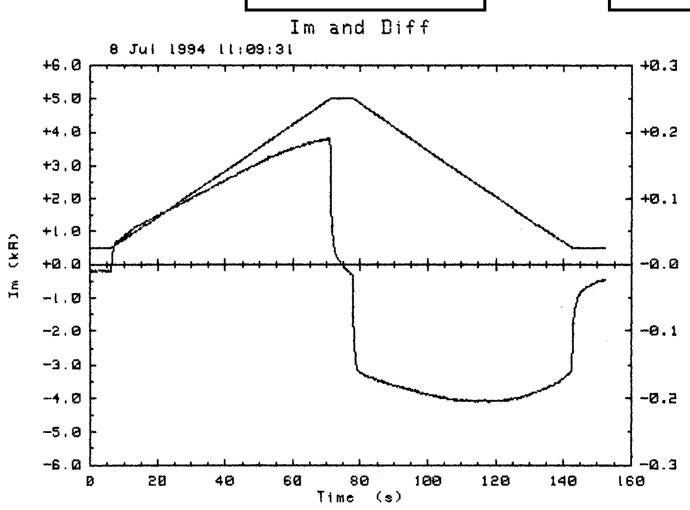
Interchanging the filters inverts the error seen in the difference signal as one might expect. I have not thought about why the errors have the amplitudes they do at the beginning and end of the up and down ramps. Presumedly, it has to do with the details of the overshoots and undershoots and how quickly the system can go from a ramp rate of 0 A/s to a ramp rate of ± 61 A/s.





The difference seen with the filters when the input signal is the current signal is shown above. The differences are smaller (<400 μV) than in the case when the input signal was the voltage. The shape of the difference signal is a bit surprising. It is also asymmetrical relative to the time of the top dwell period.





The sign of the difference is inverted when the filters are interchanged, as expected, but the shape is also somewhat different than in the preceding case. It is unclear what gives rise to these shape differences.

HP 3458A Digital Multimeters

June 16, 1994

Unit	Serial No.	Options Available	Options Installed	Remarks
1	2823A-01249	Two possible options	Option 002	
2	2823A-01255	Two possible options	Option 002	
3	2823A-02069	Two possible options	Option 002	
4	2823A-02138	Two possible options	Option 002	HP-IB Nut missing
5	2823A-03636	Four possible options	None	HP-IB Nut missing
6	2823A-03649	Four possible options	None	

Option 001 — Extended Reading Memory (expands total to 148 KB)
Option 002 — High Stability (4 ppm/year) Reference

Units 5 and 6 are later versions. The position of the chassis ground connector is different, and they have two extra possible options:

Option 700 — Control Interface Intermediate Language (CIIL) for Modular Automatic Test Equipment (MATE)
Option Special — Unspecified

Points in Fit	Intercept *(J/cycle)*	Slope $\left(\frac{J/cycle}{A/s}\right)$	Average Absolute Deviation *(J/cycle)*
DRD009			
29 September 1992 (17 points)	344	1.58	21
DRD010			
02 December 1992 (24 points)	389	0.46	25
DRE011			
13 July 1993 (21 points)	369	1.75	25
DRG102			
08 July 1994 (26 points)	340	1.16	7
DRG111			
10 June 1994 (30 points)	326	1.33	6
DCA211			
09 September 1992 (9 points)	1,230	2.79	39
DCA213			
24 July 1992 (15 points)	1,116	7.91	57
07 August 1992 (12 points)	1,141	7.76	50
All data points	1,115	7.94	54
DCA312			
23 December 1992 (17 points)	1,184	60.37	40
DCA317			
27-28 July 1993 (40 points)	1,172	3.69	39
DCA318			
19 May 1993 (24 points)	1,149	3.00	47
19 May, 01 June & 02 June 1993 (50 points)	1,135	3.85	57

AC Loss Measurements
DRG102

Ramp Rate (A/s)	Loss (J/cycle)
20	366
20.116	352.7
20.117	330.6
20.121	383.5
30.581	383.1
30.581	368.4
30.582	373.8
40.232	391.6
40.238	394.3
40.240	386.2
50.963	404.6
50.964	387.5
50.964	393.8
61.169	400.9
61.170	410.0
61.174	414.8
69.541	431.1
69.543	417.6
69.547	421.8
69.549	424.4
80.473	427.4
80.474	436.1
80.481	417.2
101.936	450.5
101.938	463.7
101.940	457.6

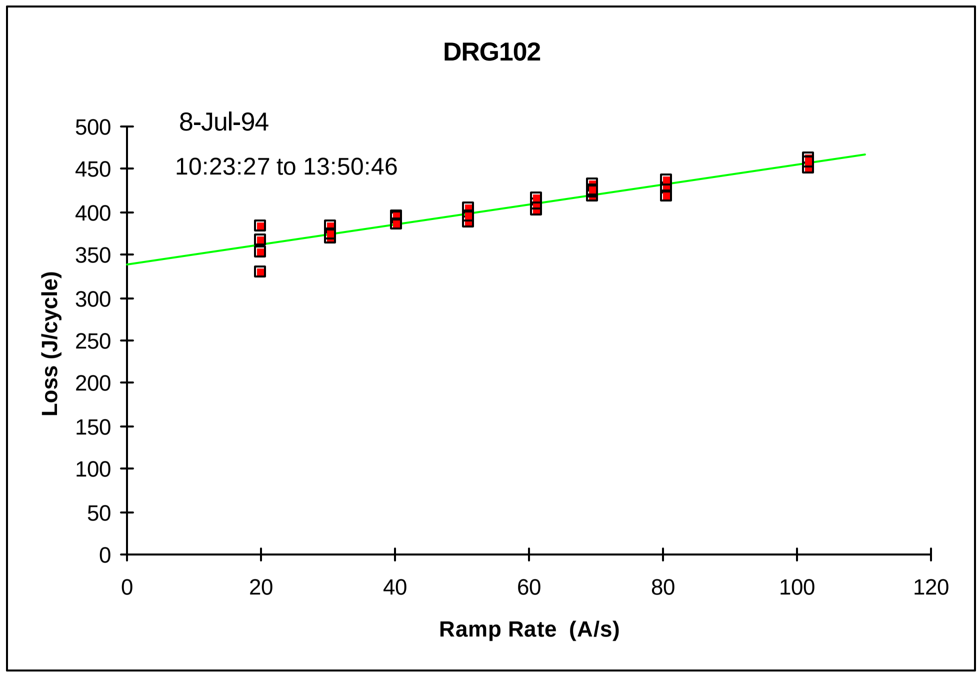
Regression Statistics

Multiple R	0.9483
R Square	0.8993
Adjusted R Square	0.8951
Standard Error	10.3572
Observations	26

Analysis of Variance

	df	*Sum of Squares*	*Mean Square*	*F*	*Significance F*
Regression	1	23001.8407	23001.8407	214.42	1.8316E-13
Residual	24	2574.5428	107.272615		
Total	25	25576.3835			

	Coefficients	*Standard Error*	*t Statistic*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 90 %*	*Upper 90 %*
Intercept	338.1	4.9	68.932	4.84E-30	328.0	348.2	329.7	346.5
Ramp Rate (A/s)	1.168	0.080	14.643	9.02E-14	1.004	1.333	1.032	1.305



BROOKHAVEN NATIONAL LABORATORY
MEMORANDUM

Date: August 1, 1994

To: Joe Muratore, Peter Wanderer, Animesh Jain, Bill Sampson, Arup Ghosh

From: Richard Thomas, 902B, ×3534, Pager 4149 (digital)

Subject: DRG103 — AC Loss Measurements

On 25 July 1994, AC loss data were acquired for the Northrop-Grumman RHIC Dipole Magnet DRG103 at ramp rates of 20, 31, 40, 51, 61, 69, 80, and 102 A/s. The results for this dipole magnet are similar to those for DRG111. The slope and intercept for the ac loss plot (loss/cycle versus ramp rate) of DRG102 were also similar to those for DRG111, but the results for DRG103 are even more similar to those for DRG111 (see Table at end).

For each ramp rate, after a dwell time at 500 A, the current is ramped up to 5000 A, a second dwell at 5000 A occurs, then the current is ramped down (at the same rate as the up ramp rate) to 500 A where another dwell occurs. The regulator card for the power supply produces overshoots at the beginning and end of the ramps. If the beginning and ending currents are identical and if the large d*I*/dt's that occur at the beginning and end of the ramps do not contribute significantly to the real losses, the overshoots probably have little effect on the computed losses. Significant amounts of inductive energy (*B*-field) do flow into and out of the magnet during the top-dwell and end-dwell periods. These dwell periods must therefore be included in the analysis.

The average real power dissipated in the magnet over the entire measurement time is calculated by summing the instantaneous power readings ($V \cdot I$). The "measurement time" includes all three dwell periods. The quantity plotted is the real energy loss which is obtained by multiplying the average real power dissipated by the measurement time.

The plots produced by the Rocky Mountain BASIC program fit the data to a line by minimizing the sum of the absolute deviations (and thus the fit is less strongly influenced by outliers). Using Excel to fit the data, which uses the conventional minimization of the sum of the squares of the deviations, gives the same intercept, 321 J/cycle, and 1.30 (J/cycle)/(A/s) for the slope (compared to 1.33). If it is assumed that the errors in the data points obtained have a normal distribution, then with 90% confidence, the intercept lies between 316 and 327 J/cycle, and the slope lies between 1.21 and 1.39 (J/cycle)/(A/s).

Eddy Current Losses of the Quench Antenna

Originally, the AC losses of DRG103 were going to be measured on 22 July 1994, but as the Quench Antenna was still present in the bore tube, there was concern that eddy current losses in the brass portions of the antenna would significantly increase the measured losses.

Measurements were however taken on that date at one ramp rate (~69 A/s) for comparison with the results taken at the same ramp rate on the following Monday with the antenna removed.

Later calculations predicted that the total losses produced by eddy currents in the Quench Antenna would be only ~0.9 J, which compared to the measured magnet loss at 69 A/s would be entirely negligible. (See Memorandum dated 29 July 1994.)

Nonetheless, the energy loss per cycle in RHIC dipole magnet DRG103 as measured on Friday, 22 July 1994, was 422 J at 69.3 A/s as compared to 404 J on Monday, 25 July 1994. The difference is only 18 J which is not much larger than the ~±6 J standard error, but can not be explained by additional losses produced by eddy currents in the Quench Antenna. The temperature of the magnet was about 0.050 kelvins higher on Friday than on Monday.

The fit of the data points taken on Monday, July 25, predict that the losses at 69.3 A/s should be 413 J (Excel) which is exactly half way between the two results obtained on the different dates at that ramp rate. Statistically, the 404 J result of July 25 was 9 J low compared to the remainder of the results obtained on that date at other ramp rates. Since measurements were taken at only one ramp rate on July 22, it is not possible to say whether that result was, statistically, high by the same amount. (The Excel least squares fit, which included the 404 J result at 69.3 A/s, gave a standard error of 5.9 J for the 21 observations at the various ramp rates. At least two measurements are taken at each ramp rate, and if these two differ from each other by more than 10 J, more measurements are taken at the same ramp rate.)

It is not clear whether the eddy current losses predicted for the Quench Antenna were as small as estimated or not, but given the statistical variation in the measurements, the results obtained do not appear to be inconsistent with the prediction.

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